FUSION-ALPHA-ENHANCED DISPLACEMENT AND STABILITY OF ITER HELICAL CORE PLASMAS

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This study investigated the interplay between fusion-born alphas and the helical core (HC)—a 3-D bifurcated MHD equilibrium characterized by a tilted magnetic axis (See Fig.1a)—in the ITER hybrid scenario. Strong pressure and current gradients in ITER, combined with weak magnetic shear, are expected to drive spontaneous HC formation, and induce core toroidal asymmetry. Motivated by this, we conducted MHD-PIC simulations under conditions close to the ITER hybrid scenario parameters. First, we find that the radial displacement of the HC magnetic axis (δ_{HC}) tends to be enhanced by alphas even in regimes where the alphas reduce the HC linear growth rate (γ_{HC}). The enhanced δ_{HC} can exceed 0.4 m, significantly shifting the plasma across diagnostic sightlines. Second, we find that some HC states are prone to secondary instabilities – here in the form of resistive pressure-driven MHD modes – capable of causing radial mixing of both alphas and bulk plasma. These results highlight the necessity to reassess ITER's hybrid scenario by accounting for global nonlinear 3-D and kinetic effects, including fusion-born alpha particles and other fast ion populations.

1. INTRODUCTION

A hybrid scenario is a tokamak configuration with weak core magnetic shear and a safety factor near unity ($q \gtrsim 1$). This configuration is a candidate for long-pulse operation in ITER because it may require little to no control due to the self-organization via internal kink/quasi-interchange modes. Meanwhile, the coherent growth and saturation of these modes can form a HC [1-3]. A HC can have both positive and negative effects on plasma performance, diagnostics, and control. Hence, a good understanding and predictive capability are essential for utilizing or mitigating a HC as needed. Prior studies of HC plasmas using VMEC [4], a 3-D equilibrium solver based on ideal MHD energy minimization, predicted that HC can spontaneously form in ITER and reach core displacements δ_{HC} as large as 0.4 m [2-3]. It has been shown that HC onset criteria and the value of δ_{HC} depend on the plasma shape, q profile, and plasma pressure [2,3,5]. However, the effects of fusion-born alphas, whose normalized pressure is expected to reach a significant value of $\beta_\alpha \sim 1\%$ in ITER, remained unexplored. It is known that fast ions like fusion-born alphas can affect the linear stability of kink/quasi-interchange modes, thereby affecting the HC. This raises two questions: (i) Can HC form in the presence of alphas, and if so, how do they modify the HC? (ii) How does the HC affect alpha confinement?

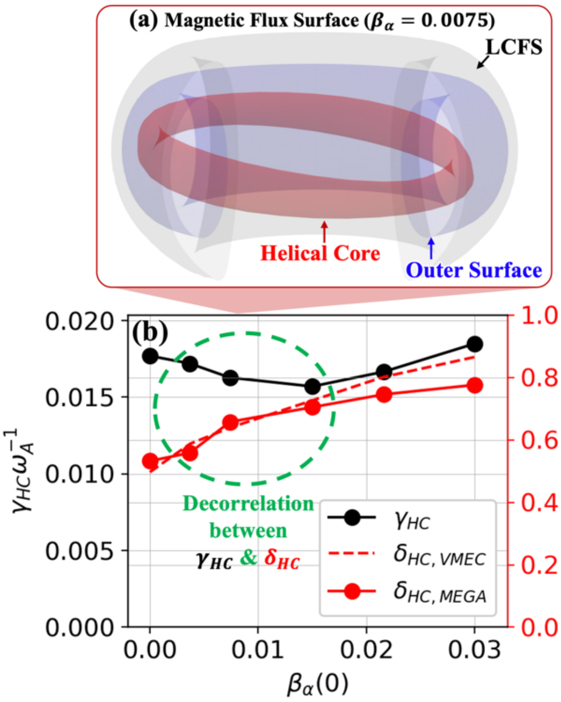

Fig.1 (a) Magnetic flux surfaces in a HC equilibrium, (b) Dependencies of the HC linear growth γ_{HC}, left axis, and saturated displacement δ_{HC}, right axis, on the normalized alpha pressure β_α in the ITER-like hybrid scenario with q_0/ρ_{qmin}=1.1/0.57

2. METHODOLOGY

We use MEGA [6], a nonlinear PIC-MHD simulation code, with dynamics constrained to toroidal mode numbers $n \leq 8$. The HC states predicted by MEGA are also compared to those of VMEC. In MEGA, we model the alphas using a full-f PIC method, suitable for large perturbations and accounting for both fluid-like and kinetic interactions. In contrast, VMEC captures the effect of alphas only via their contribution to the total MHD scalar pressure. The initial axisymmetric equilibrium, including bulk plasma pressure, density, and shape, is based on the ITER hybrid scenario calculated by CORSICA [7]. However, we varied the central safety factor (q_0) and radial position of q_{min} (ρ_{qmin}) within 1.06≤ q_0 ≤1.2 and 0.45 ≤ ρ_{qmin} ≤ 0.67, respectively.

3. SIMULATION RESULTS

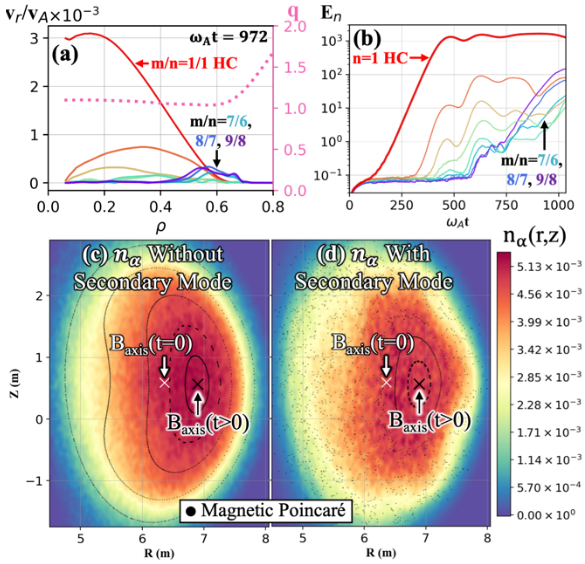

Fig. 2 (a) Radial MHD velocity profile and (b) time evolution of mode energies, highlighting the emergence of secondary modes after HC formation, with times normalized by the Alfvén frequency ω_A. (c-d) Poloidal cross-section of alpha density after HC formation, comparing cases without and with secondary modes. Black markers indicate the magnetic Poincaré plot.

All the ITER equilibria studied here were linearly unstable (far from the bifurcation threshold) to the m/n=1/1 kink/quasi-interchange mode, where m is the poloidal mode number. First, we verified that the HC states predicted by MEGA and VMEC quantitatively agree in the absence of alphas. δ_{HC} is plotted in Fig.1(b), showing the agreement between $\delta_{HC,MEGA}$ and $\delta_{HC,VMEC}$ at $\beta_\alpha = 0$. Although only one case is shown, this level of agreement held over the entire range of scanned equilibria. The alpha pressure was then scanned up to $\beta_\alpha \leq 3\%$. Within ITER's operating range, $\beta_\alpha \lesssim 1\%$, alphas weakly reduce the linear growth rate (γ_{HC}), relative to the axisymmetric equilibrium, by roughly 10%. Meanwhile, δ_{HC} increases monotonically with β_α, as indicated by the green dashed circle in Fig.1(b). The decorrelation between γ_{HC} and δ_{HC}, along with the agreement $\delta_{HC,MEGA} \approx \delta_{HC,VMEC}$ for $\beta_\alpha \leq 1\%$ implies weak kinetic effects and that γ_{HC} is influenced by kinetic and other non-ideal effects, whereas δ_{HC} is dominated by quasi-linear effects. During the HC formation in MEGA, the pressure profiles of the MHD bulk plasma and alphas are gradually deformed but without any observable gradient flattening or reconnection. For $\beta_\alpha \gtrsim 1.5\%$, VMEC predicts a higher δ_{HC} than MEGA, suggesting that the kinetic and other non-ideal effects become significant.

After HC formation, we often observe the growth of secondary $n \gtrsim 6$ modes, as shown in Figs.2(a-b) (See m/n=7/6, 8/7, and 9/8). These modes are localized near the q_{min} region. Due to their multiple helicities and spatial overlap, these modes can lead to a stochastization of the magnetic field lines and alpha trajectories. Figs. 2(b) and (c) show the poloidal cross-section of the alpha density after HC formation, comparing the case without (low-pass-filtered) and with secondary modes, respectively. The magnetic Poincaré plot is overlaid as black-filled markers. In the case without secondary mode, alpha trajectories remain connected on helically distorted but nested toroidal surfaces. In contrast, the alpha density profile becomes broadened in the presence of secondary modes. Systematic parameter scans revealed that these secondary modes are a kind of resistive pressure-driven MHD modes, and they become unstable when the size of the low magnetic q≳1 region exceeds a threshold.

4. CONCLUSION

The results reported in this study advance our understanding of helical cores (HC) in burning plasmas. We confirmed that the HC can form spontaneously in the presence of alphas in ITER conditions and demonstrated that the alphas tend to enhance δ_{HC}. Our benchmarks show that a 3-D equilibrium code like VMEC can yield a consistent result with MEGA in ITER with $\beta_\alpha \lesssim 1\%$ included in the scalar MHD pressure, at least when the plasma is far from the bifurcation threshold and the alpha kinetic effect is sufficiently weak. Our MHD-PIC simulations show that alphas remain well-confined after HC formation only in the absence of secondary modes. Secondary short-wavelength modes need to be examined further, preferably using turbulence codes. Cases where steep alpha pressure gradients are maintained may be subject to resonantly-driven MHD modes that are under investigation using MEGA. These results will be valuable for the design, diagnostics, and control of hybrid scenarios for burning plasmas in various devices, including ITER.

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